# Environmental Protection Series

## National Inventory of Sources and Emissions of Carbon Dioxide

Report EPS 5/AP/2
May 1990

Canada

Environment Canada | Environnement Canada

90-05430/

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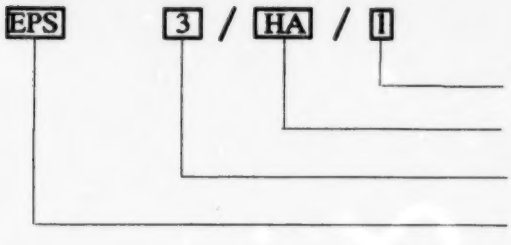


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# NATIONAL INVENTORY OF SOURCES AND EMISSIONS OF CARBON DIOXIDE (1987)

A.P. Jaques
Environmental Protection
Conservation and Protection
Environment Canada

EPS 5/AP/2
May 1990

**Canadian Cataloguing in Publication Data**

Jaques, A. P

National inventory of sources and emissions of carbon dioxide (1987)

(Report ; EPS 5/AP/2E)
Includes an abstract in French.
Includes bibliographical references.
Issued by Conservation and Protection.
ISBN 0-662-17590-5
DSS cat. no. En49-5/5-2E

1. Carbon dioxide -- Environmental aspects.
2. Pollution -- Measurement. 3. Canada -- Industries -- Environmental aspects. I. Canada. Environment Canada. II. Canada. Conservation and Protection. III. Title. IV. Series: Report (Canada. Environment Canada) ; EPS 5/AP/2E.

TD885.5.C3J63 1990 363.7'28 C90-098570-4

©Minister of Supply and Services Canada 1990
Catalogue No. En 49-5/5-2E
ISBN 0-662-17590-5
BEAUREGARD PRINTERS LIMITED

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## ABSTRACT

Estimates of the quantities of carbon dioxide released to the environment as emissions in 1987 are summarized in this report. Emissions have been classified by source, sector, province, and fuel type. The data presented are estimates based on sampling data, production figures, and stoichiometric equations. Total anthropogenic emissions of carbon dioxide in 1987 were estimated to be 128 Mt of carbon with stationary combustion sources accounting for 71 Mt or 55% of the total.

A brief summary of the sources of carbon dioxide is included as is a detailed analysis of the methods used in estimating emissions.

## RÉSUMÉ

Les estimations des quantités de dioxyde de carbone dégagées dans l'environnement sous forme d'émissions en 1987 sont résumées dans le présent rapport. Les émissions ont été classifiées par source, secteur, province et type de combustible. Les données présentées sont des estimations fondées sur des données d'échantillonnage, des données sur la production et des équations stoechiométriques. En 1987, les émissions anthropiques de dioxyde de carbone étaient estimées à 128 mt de carbone, les sources fixes de combustion comptant pour 71 mt, soit 55 p. 100 du total.

Ce rapport comprend un résumé concis du dioxyde de carbone ainsi qu'une analyse détaillée des méthodes utilisées pour estimer les émissions.

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## SUMMARY

This inventory identifies anthropogenic sources of carbon dioxide released to the environment as emissions. For the purposes of this report, emissions have been defined as gaseous releases to the atmosphere. In addition, all emissions have been reported as tonnes of carbon to facilitate comparison with other published estimates as well as to put into perspective the magnitude of anthropogenic emissions with the global carbon flux. All emission estimates may be converted to tonnes of carbon dioxide by multiplying by 44/12.

Emissions of carbon dioxide in Canada for 1987 have been estimated and are shown in Table S.1 as tonnes of carbon and in Table S.2 as tonnes of carbon dioxide. Figures S.1 and S.2 provide a breakdown of emissions by province and source.

In 1987, of the total emissions of carbon dioxide contributed by Canadians (128 Mt), approximately 30% were from transportation sources, 20% from power generation, 23% from natural gas combustion, 6% from the combustion of spent pulping liquors, 5% from wood combustion, and the remainder from cement and ammonia production, incineration, and the combustion of fuel oils.

Emissions are projected to increase by almost 40% from 1985 to 2005.

TABLE S.1 SUMMARY OF EMISSIONS OF CARBON DIOXIDE IN CANADA FOR 1987 (tonnes of carbon)

| Sector | Nfld. | P.E.I. | N.S. | N.B. | Que. |
|---|---|---|---|---|---|
| **Industrial Sources** | | | | | |
| Cement Production | 21 899 | 0 | 42 289 | 27 580 | 514 479 |
| Ammonia Production | 0 | 0 | 0 | 0 | 0 |
| Pulp and Paper Production | 0 | 0 | 219 272 | 627 337 | 1 372 311 |
| **Fuel Combustion - Stationary Sources** | | | | | |
| Gas plant/field use | 0 | 0 | 0 | 0 | 0 |
| Power Generation | 523 602 | 20 394 | 1 746 122 | 1 109 914 | 58 337 |
| Residential | 149 721 | 78 082 | 485 872 | 217 454 | 1 660 383 |
| Commercial | 57 548 | 25 507 | 151 349 | 91 288 | 999 847 |
| Industrial | 354 840 | 12 509 | 339 236 | 383 273 | 2 717 012 |
| Agriculture | 3 950 | 5 292 | 17 282 | 13 262 | 75 418 |
| Public Administration | 22 013 | 8 836 | 86 850 | 55 771 | 73 184 |
| Fuel Wood | 201 542 | 103 660 | 106 911 | 121 720 | 923 913 |
| **Fuels Combustion - Transportation Sources** | | | | | |
| **Gasoline** | | | | | |
| Autos | 228 553 | 67 958 | 451 666 | 379 728 | 2 803 370 |
| LDV's | 96 642 | 28 735 | 190 983 | 160 564 | 1 185 378 |
| HDV's | 25 083 | 7 458 | 49 568 | 41 673 | 307 655 |
| Motorcycles | 1 019 | 303 | 2 013 | 1 693 | 12 496 |
| **Diesel** | | | | | |
| LDV's | 11 500 | 1 654 | 14 074 | 16 371 | 113 539 |
| HDV's | 103 274 | 14 850 | 126 381 | 147 008 | 1 019 585 |
| Other | 79 569 | 12 648 | 177 916 | 83 829 | 585 013 |
| Railroads | 10 122 | 1 195 | 47 024 | 35 598 | 133 475 |
| Marine | 120 072 | 7 751 | 230 263 | 85 736 | 479 383 |
| Aircraft | 205 838 | 5 471 | 118 060 | 22 082 | 676 054 |
| Off-road gas | 6 582 | 5 321 | 15 907 | 19 782 | 102 322 |
| Natural Gas | 0 | 0 | 0 | 0 | 10 081 |
| Propane | 457 | 539 | 3 786 | 2 791 | 29 670 |
| **Solid Waste Incineration** | | | | | |
| Municipal | 0 | 6 752 | 0 | 0 | 141 349 |
| Industrial | 2 356 | 620 | 8 680 | 11 111 | 31 374 |
| Wood Waste | 4 361 | 1 846 | 22 500 | 52 122 | 432 692 |
| **Miscellaneous Sources** | | | | | |
| Slash Burning | 63 774 | 10 570 | 87 403 | 200 596 | 899 469 |
| TOTAL | 2 294 304 | 427 949 | 4 741 408 | 3 908 083 | 17 357 792 |

| Ont. | Man. | Sask. | Alta. | B.C. | NWT/YUK | National | % of Total |
|---|---|---|---|---|---|---|---|
| 602 181 | 63 180 | 91 003 | 195 166 | 156 264 | 0 | 1 714 030 | 1.33 |
| 264 802 | 44 134 | 0 | 728 204 | 66 200 | 0 | 1 103 340 | 0.86 |
| 1 547 791 | 99 809 | 221 726 | 398 589 | 3 975 237 | 0 | 8 462 072 | 6.59 |
| 0 | 0 | 603 680 | 5 306 017 | 389 725 | 65 081 | 6 364 503 | 4.96 |
| 8 261 850 | 209 614 | 3 312 601 | 10 348 818 | 116 176 | 48 979 | 25 756 406 | 20.05 |
| 4 313 933 | 325 253 | 548 220 | 1 624 247 | 926 899 | 15 165 | 10 345 231 | 8.05 |
| 2 082 116 | 315 681 | 291 481 | 1 042 206 | 678 686 | 31 411 | 5 767 119 | 4.49 |
| 9 866 145 | 332 832 | 629 634 | 2 826 833 | 1 709 649 | 54 435 | 19 226 397 | 14.97 |
| 183 240 | 13 838 | 46 159 | 116 784 | 42 801 | 496 | 518 521 | 0.40 |
| 172 198 | 9 278 | 22 193 | 45 906 | 42 605 | 50 226 | 589 060 | 0.46 |
| 785 579 | 44 787 | 54 178 | 35 757 | 88 852 | 30 701 | 2 497 600 | 1.94 |
| 5 007 543 | 540 890 | 592 262 | 1 633 405 | 1 440 688 | 40 686 | 13 186 748 | 10.27 |
| 2 117 392 | 228 710 | 250 432 | 690 670 | 609 181 | 17 203 | 5 575 891 | 4.34 |
| 549 552 | 59 360 | 64 998 | 179 258 | 158 108 | 4 465 | 1 447 178 | 1.13 |
| 22 321 | 2 411 | 2 640 | 7 281 | 6 422 | 181 | 58 779 | 0.05 |
| 199 918 | 23 478 | 30 927 | 89 549 | 83 628 | 4 729 | 589 367 | 0.46 |
| 1 795 273 | 210 832 | 277 726 | 804 156 | 750 984 | 42 468 | 5 292 537 | 4.12 |
| 734 799 | 215 570 | 478 780 | 773 957 | 634 138 | 67 114 | 3 843 333 | 2.99 |
| 344 476 | 201 052 | 96 419 | 387 123 | 214 047 | 1 350 | 1 471 681 | 1.15 |
| 265 282 | 19 | 0 | 212 | 234 606 | 135 | 1 423 460 | 1.11 |
| 1 062 532 | 139 950 | 63 016 | 478 008 | 519 325 | 56 506 | 3 346 843 | 2.61 |
| 179 245 | 91 013 | 280 418 | 309 229 | 63 963 | 7 435 | 1 081 216 | 0.84 |
| 473 613 | 127 221 | 277 423 | 222 640 | 195 825 | 0 | 1 306 803 | 1.02 |
| 161 862 | 11 832 | 12 909 | 88 128 | 64 448 | 1 420 | 377 841 | 0.29 |
| 63 888 | 0 | 0 | 0 | 9 625 | 0 | 223 614 | 0.17 |
| 46 006 | 5 208 | 4 712 | 12 277 | 14 261 | 372 | 136 978 | 0.11 |
| 222 824 | 55 037 | 25 414 | 117 579 | 1 508 503 | 0 | 2 442 876 | 1.90 |
| 717 141 | 43 626 | 76 656 | 228 138 | 1 953 062 | 4 726 | 4 285 160 | 3.34 |
| 42 045 501 | 3 414 615 | 8 355 606 | 28 690 136 | 16 653 906 | 545 282 | 128 434 582 | 100.00 |

TABLE 5.2 SUMMARY OF EMISSIONS OF CARBON DIOXIDE IN CANADA FOR 1987 (tonnes of carbon dioxide)

| Sector | Nfld. | P.E.I. | N.S. | N.B. | Que. |
|---|---|---|---|---|---|
| **Industrial Sources** | | | | | |
| Cement Production | 80 259 | 0 | 155 060 | 101 127 | 1 886 424 |
| Ammonia Production | 0 | 0 | 0 | 0 | 0 |
| Pulp and Paper Production | 0 | 0 | 803 997 | 2 300 236 | 5 031 807 |
| **Fuel Combustion - Stationary Sources** | | | | | |
| Gas plant/field use | 0 | 0 | 0 | 0 | 0 |
| Power Generation | 1 919 874 | 74 777 | 6 402 448 | 4 069 684 | 213 903 |
| Residential | 548 975 | 286 302 | 1 781 530 | 797 333 | 6 088 071 |
| Commercial | 211 010 | 93 525 | 554 946 | 334 721 | 3 666 107 |
| Industrial | 1 301 079 | 45 865 | 1 243 864 | 1 405 336 | 9 962 379 |
| Agriculture | 14 484 | 19 404 | 63 367 | 48 629 | 276 531 |
| Public Administration | 80 713 | 32 397 | 318 449 | 204 492 | 268 342 |
| Fuel Wood | 738 986 | 380 088 | 392 008 | 446 305 | 3 387 682 |
| **Fuels Combustion - Transportation Sources** | | | | | |
| **Gasoline** | | | | | |
| Autos | 838 028 | 249 179 | 1 656 110 | 1 392 335 | 10 279 024 |
| LDV's | 354 352 | 105 363 | 700 270 | 588 736 | 4 346 387 |
| HDV's | 91 969 | 27 346 | 181 749 | 152 802 | 1 128 070 |
| Motorcycles | 3 735 | 1 111 | 7 382 | 6 206 | 45 818 |
| **Diesel** | | | | | |
| LDV's | 42 168 | 6 063 | 51 603 | 60 025 | 416 310 |
| HDV's | 378 670 | 54 450 | 463 398 | 539 030 | 3 738 479 |
| Other | 291 751 | 46 375 | 652 358 | 307 375 | 2 145 048 |
| Railroads | 37 114 | 4 383 | 172 421 | 129 793 | 489 410 |
| Marine | 440 264 | 28 419 | 844 299 | 314 367 | 1 757 738 |
| Aircraft | 754 738 | 20 062 | 432 888 | 80 968 | 2 478 865 |
| Off-road gas | 24 133 | 19 510 | 58 327 | 72 535 | 375 182 |
| Natural Gas | 0 | 0 | 0 | 0 | 36 964 |
| Propane | 1 676 | 1 975 | 13 883 | 10 233 | 108 789 |
| **Solid Waste Incineration** | | | | | |
| Municipal | 0 | 24 757 | 0 | 0 | 518 280 |
| Industrial | 8 639 | 2 274 | 31 828 | 40 741 | 115 037 |
| Wood Waste | 15 990 | 6 767 | 82 500 | 191 114 | 1 586 537 |
| **Miscellaneous Sources** | | | | | |
| Slash Burning | 233 838 | 38 755 | 320 478 | 735 519 | 3 298 052 |
| Total | 8 412 447 | 1 569 147 | 17 385 164 | 14 329 639 | 63 645 236 |

| Ont. | Man. | Sask. | Alta. | B.C. | NWT/YUK | National | % of Total |
|---|---|---|---|---|---|---|---|
| 2 207 997 | 231 660 | 333 676 | 715 607 | 572 967 | 0 | 6 284 778 | 1.33 |
| 970 941 | 161 825 | 0 | 2 670 081 | 242 733 | 0 | 4 045 580 | 0.86 |
| 5 675 234 | 365 966 | 812 995 | 1 461 493 | 14 575 869 | 0 | 31 027 597 | 6.59 |
| 0 | 0 | 2 213 492 | 19 455 397 | 1 428 992 | 238 629 | 23 336 510 | 4.96 |
| 30 293 450 | 768 586 | 12 146 203 | 37 945 667 | 425 978 | 179 588 | 94 440 157 | 20.05 |
| 15 817 755 | 1 192 596 | 2 010 140 | 5 955 573 | 3 398 631 | 55 606 | 37 932 512 | 8.05 |
| 7 634 426 | 1 157 498 | 1 068 764 | 3 821 421 | 2 488 514 | 115 173 | 21 146 105 | 4.49 |
| 36 175 866 | 1 220 384 | 2 308 657 | 10 365 055 | 6 268 711 | 199 595 | 70 496 790 | 14.97 |
| 671 880 | 50 739 | 169 249 | 428 207 | 156 936 | 1 817 | 1 901 243 | 0.40 |
| 631 394 | 34 020 | 81 376 | 168 321 | 156 219 | 184 162 | 2 159 886 | 0.46 |
| 2 880 457 | 164 220 | 198 651 | 131 110 | 325 789 | 112 570 | 9 157 865 | 1.94 |
| 18 360 989 | 1 983 262 | 2 171 629 | 5 989 150 | 5 282 523 | 149 180 | 48 351 410 | 10.27 |
| 7 763 769 | 838 604 | 918 252 | 2 532 455 | 2 233 664 | 63 079 | 20 444 932 | 4.34 |
| 2 015 024 | 217 653 | 238 325 | 657 278 | 579 730 | 16 372 | 5 306 318 | 1.13 |
| 81 843 | 8 840 | 9 680 | 26 696 | 23 546 | 665 | 215 523 | 0.05 |
| 733 033 | 86 085 | 113 399 | 328 347 | 306 636 | 17 340 | 2 161 011 | 0.46 |
| 6 582 667 | 773 051 | 1 018 330 | 2 948 572 | 2 753 607 | 155 717 | 19 405 969 | 4.12 |
| 2 694 264 | 790 422 | 1 755 528 | 2 837 842 | 2 325 174 | 246 083 | 14 092 221 | 2.99 |
| 1 263 078 | 737 190 | 353 537 | 1 419 451 | 784 837 | 4 949 | 5 396 164 | 1.15 |
| 972 700 | 71 | 0 | 778 | 860 223 | 495 | 5 219 352 | 1.11 |
| 3 895 949 | 513 149 | 231 058 | 1 752 698 | 1 904 193 | 207 188 | 12 271 756 | 2.61 |
| 657 231 | 333 714 | 1 028 198 | 1 133 838 | 234 531 | 27 260 | 3 964 458 | 0.84 |
| 1 736 582 | 466 477 | 1 017 217 | 816 347 | 718 024 | 0 | 4 791 610 | 1.02 |
| 593 493 | 43 384 | 47 333 | 323 136 | 236 308 | 5 206 | 1 385 416 | 0.29 |
| 241 590 | 0 | 0 | 0 | 35 291 | 0 | 819 918 | 0.17 |
| 168 690 | 19 097 | 17 279 | 45 014 | 52 290 | 1 364 | 502 233 | 0.11 |
| 817 020 | 201 802 | 93 183 | 431 122 | 5 531 177 | 0 | 8 957 212 | 1.90 |
| 2 629 516 | 159 961 | 281 072 | 836 507 | 7 161 227 | 17 329 | 15 712 255 | 3.34 |
| 154 166 838 | 12 520 254 | 30 637 223 | 105 197 164 | 61 064 323 | 1 999 367 | 470 926 800 | 100.00 |

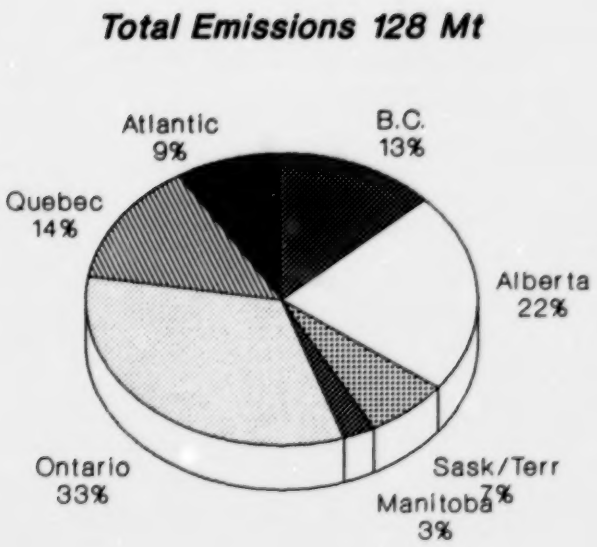



FIGURE S.1 CARBON DIOXIDE EMISSIONS BY REGION (1987)

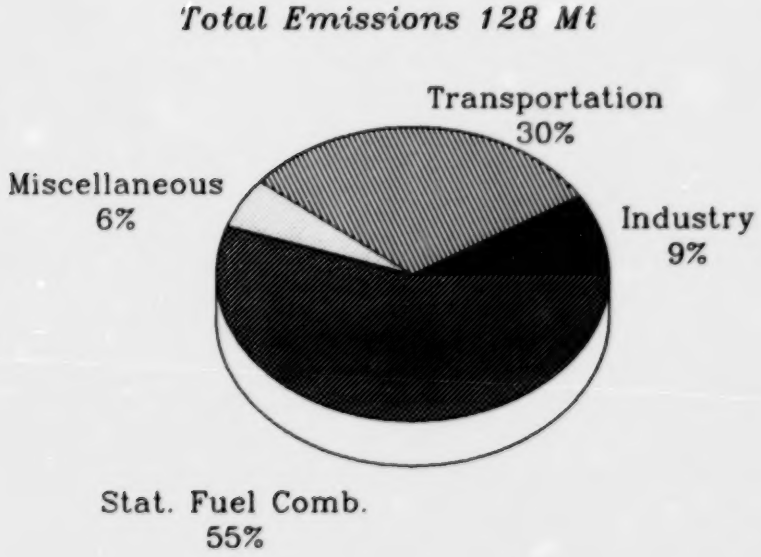



FIGURE S.2 CARBON DIOXIDE EMISSIONS BY SECTOR (1987)

TABLE S.3 CARBON DIOXIDE EMISSION FACTORS

| Fuel Type | Emission Factors | | |
|---|---|---|---|
| | Carbon | Carbon | Carbon Dioxide |
| **Gaseous Fuels** | ($g/m^3$) | (t/TJ) | (t/TJ) |
| Natural gas | 512.46 | 13.55 | 49.68 |
| **Liquid Fuels** | (g/L) | | |
| Motor gasoline | 642.60 | 18.54 | 67.98 |
| Kerosene | 695.20 | 18.45 | 67.65 |
| Aviation gasoline | 634.20 | 18.92 | 69.37 |
| Propane | 416.65 | 16.32 | 59.84 |
| Diesel Oil | 745.75 | 19.28 | 70.69 |
| Light Oil | 771.28 | 19.94 | 73.11 |
| Heavy Oil | 814.15 | 19.51 | 71.54 |
| Aviation Turbo | 694.17 | 19.32 | 70.84 |
| **Solid Fuels** | (g/kg) | | |
| U.S. Bituminous | 702.97 | 24.25 | 88.90 |
| Cdn. Bituminous | 692.95 | 25.12 | 92.10 |
| Sub-bituminous | 507.63 | 27.00 | 99.00 |
| Lignite | 425.66 | 29.56 | 108.40 |
| Petroleum Coke | 898.92 | 25.75 | 94.42 |
| Fuel Wood | 400.00 | 22.22 | 81.47 |
| Slash Burning | 400.00 | 22.22 | 81.47 |
| Incineration | 250.00 | - | - |
| **Industrial Sources** | (g/kg) | - | - |
| Cement Production | 140.00[a] | - | - |
| Ammonia Production | 430.00[b] | - | - |
| Pulp and Paper Production | 410.00[c] | 29.29 | 107.38 |

a - of cement produced
b - of ammonia produced
c - of spent pulping liquors consumed

# 1 INTRODUCTION

The purpose of this report is to identify and quantify anthropogenic sources of emissions of carbon dioxide ($CO_2$) in Canada for the year 1987 and to provide a methodology for estimating emissions. Information was obtained from numerous sources, including: published reports, personal communication, and engineering calculations.

The major sources of $CO_2$ arise from the combustion of fossil fuels. Total man-made emissions of $CO_2$ (expressed as carbon), were estimated to be 128 Mt in 1987. This figure differs somewhat from that calculated by the U.S. Department of Energy which estimated Canadian emissions to be 111 Mt in 1987 (Marland, 1989). The difference can be attributed almost entirely to the inclusion of sources other than fossil fuels and use of consumption data instead of production data.

Most estimates of $CO_2$ emissions do not contain figures for the burning of biomass, which includes wood combustion, slash burning, woodwaste incineration, and agricultural waste burning. The argument against inclusion of these figures is that since biomass is a renewable source of energy there is no net emission of carbon. This argument is valid only for those cases in which the quantity of carbon released to the environment balances the quantity removed. As far as harvesting of Canadian forests is concerned (see Section 5), this is simply not the case. In this report an attempt has been made to include all man-made sources of $CO_2$ released to the environment, regardless of natural sinks; therefore, all anthropogenic sources have been included in the totals.

In addition to a breakdown by province and sector (Table S.1), emissions have been estimated on a fuel basis under solids, liquids, and gases (Figure 1 and Table 1).

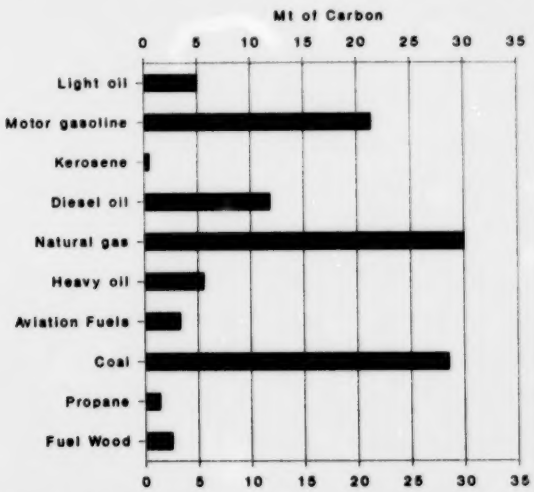



FIGURE 1 CARBON DIOXIDE EMISSIONS BY FUEL (1987)

TABLE 1 CARBON DIOXIDE EMISSIONS BY FUEL AND PROCESS

| Fuel/Process | Emissions (Mt) | Percent of Total (%) |
|---|---|---|
| **Gaseous Fuels** | | |
| Natural gas | 30.12 | 23.45 |
| **Liquid Fuels** | | |
| Motor Gasoline | 21.34 | 16.61 |
| Kerosene | 0.50 | 0.39 |
| Aviation Gasoline | 0.11 | 0.09 |
| Propane | 1.40 | 1.09 |
| Diesel Oil | 11.83 | 9.21 |
| Light Oil | 4.95 | 3.85 |
| Heavy Oil | 5.56 | 4.33 |
| Aviation Turbo | 3.23 | 2.51 |
| **Solid Fuels** | | |
| U.S. Bituminous | 10.19 | 7.93 |
| Cdn. Bituminous | 4.41 | 3.43 |
| Sub-bituminous | 9.40 | 7.32 |
| Lignite | 4.30 | 3.35 |
| Anthracite | 0.22 | 0.17 |
| Fuel Wood | 2.50 | 1.95 |
| Slash Burning | 4.29 | 3.34 |
| Incineration | 2.80 | 2.18 |
| **Industrial Processes** | | |
| Cement Production | 1.74 | 1.35 |
| Ammonia Production | 1.10 | 0.86 |
| Spent Pulping Liquor | 8.46 | 6.59 |
| **Total Emissions** | 128.45 | 100.00 |

## 2 BACKGROUND

The concentration of carbon dioxide, a trace gas in the earth's atmosphere, oscillates naturally due to annual variations in biological activity. While natural emission and removal processes are more or less in equilibrium, increasing concentrations of $CO_2$ can be seen superimposed on the seasonal fluctuations. Man's contribution from burning fossil fuels, harvesting forests, and converting land to agricultural use, has been more than sufficient to explain the increases in atmospheric concentrations (Pales and Keeling, 1965; Robinson and Robbins, 1972). Although the additional input of non-fossil fuel $CO_2$ from forest cutting and burning and soil management practices is relatively unknown, it may be as significant as that emitted from the burning of fossil fuels (Bolin et al., 1979: Zimen, 1979; Woodwell, 1978).

Only about half the electromagnetic radiation in the visible spectrum entering the atmosphere is absorbed by clouds and particles or reflected back to space. The remainder is absorbed at the earth's surface, warming the oceans and land. The warmed surfaces then reradiate this energy in the form of heat. Carbon dioxide is one of the most important infrared absorbers in the wavelength ranges of 550 to 800 $cm^{-1}$; 850 to 1100 $cm^{-1}$; and 2100 to 2400 $cm^{-1}$ (Wuebbles and Edmonds, 1987). This phemonenon, commonly referred to as the "greenhouse effect", is responsible for keeping the earth's surface about 30°C warmer than it would be without an atmosphere (EPRI, 1986).

Carbon dioxide and other naturally occurring gases in the atmosphere do not absorb all infrared wavelengths, some of the heat radiated by the planet escapes back to space. As a result, even with increasing levels of $CO_2$, the atmosphere is relatively transparent to radiation with wavelengths between 7 and 12 $\mu m$. It is in this range, though, that many of the other greenhouse gases such as methane, ozone, nitrous oxide and several chlorofluorocarbons (CFCs) are powerful absorbers (EPRI, 1986). Consequently, reducing carbon dioxide levels alone may not be sufficient to reduce the current trend towards global warming.

Although scientists have been aware of the growing concentrations of $CO_2$ in the atmosphere for many years, it was not until 1957-58 that the first $CO_2$-monitoring program was started and accurate measurements taken, at sites that are believed to represent a well-mixed state of the atmosphere: Mauna Loa, Hawaii, and the South Pole.

Since that time, the atmospheric $CO_2$ concentration has increased by about 10%. In 1989 the average concentration of $CO_2$ in the atmosphere was 350 ppm (Graedel and Crutzen, 1989), an increase of about 21% from the pre-industrial level of 290 ppm

(Bolin et al., 1979) and an increase of 35 ppm from 1958 levels. Assuming $5.14 \times 10^{21}$ g as the mass of the atmosphere (Bolin et al., 1979) and 29 as the mole weight of air, 350 ppm translates to $745 \times 10^{9}$ tonnes of $CO_2$ as carbon.

Based on the measured increase in atmospheric $CO_2$, it has been estimated that approximately half of the annual emissions from fossil fuel combustion (or 2500 Mt of carbon per year) accumulates in the atmosphere. The rest is thought to be consumed by plants and absorbed by the oceans.

It has been commonly assumed that the cause of the long-term $CO_2$ increase is industrial activities in which $CO_2$ is produced, either through the combustion of fossil fuels or industrial processes such as the manufacture of cement, ammonia, and paper. This appears to be the case in Canada at least, where these sources account for about 93% of the total man-made emissions of carbon dioxide. The remaining 7% can be attributed to wood combustion and incineration.

To put Canada's emissions of $CO_2$ into perspective, fossil fuel emissions should be compared with those from the rest of the world. Present emissions of $CO_2$ in Canada from fossil fuel combustion are about 111 Mt of carbon. This corresponds to about 2% of the global estimate of 5650 Mt (Marland, 1989). In 1986, however, Canada ranked fourth in the world with emissions estimated at 4.094 tonnes per capita (CDIAC, 1988). This is only behind the German Democratic Republic, the United States, and Czechoslovakia. The differences in fossil fuel derived emissions of $CO_2$ between developed and developing countries are illustrated in Figure 2.

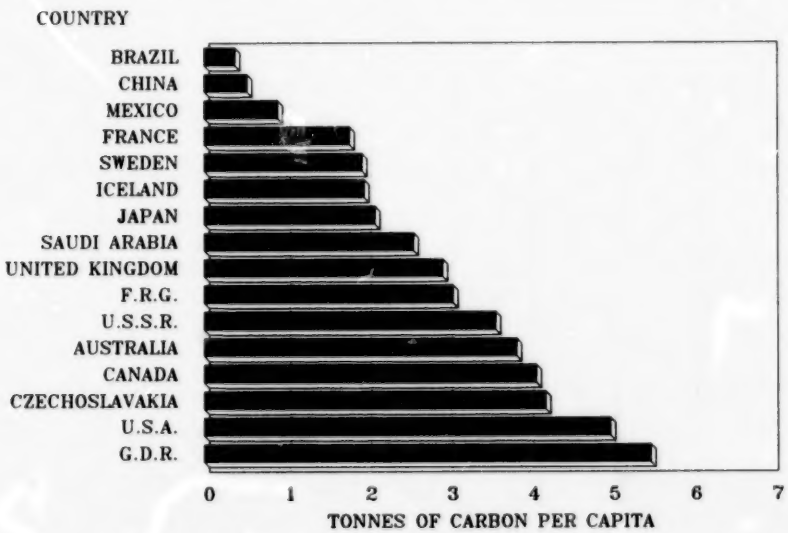



FIGURE 2 EMISSIONS OF CARBON DIOXIDE PER CAPITA (as carbon)

# 3 METHODOLOGY

Carbon dioxide is one of the end-products from the combustion of organic materials such as coal, petroleum, gas, and wood, and the incineration of waste materials. Inorganic carbonates also decompose thermally to yield carbon dioxide as well as other oxides.

Since $CO_2$ is produced when a fuel is burned, the calculation of $CO_2$ emissions should be straightforward. The following equation illustrates this:

$$C_xH_y + (X + 1/4Y)\,O_2 \rightarrow X\,CO_2 + 1/2\,YH_2O + \Delta H$$

where: $\Delta H$ is the heat of reaction, and

$C_xH_y$ is a generalized hydrocarbon fuel

For each type of fuel burned, the annual $CO_2$ emissions can be expressed as the product of three parameters: the amount of fuel consumed; the carbon content of the fuel; and the fraction of the fuel oxidized.

In addition, for purposes of simplification, emissions from fossil fuels have been estimated using three classes of fuels: gaseous, liquid, and solid. This method is similar to that used by Marland and Rotty (1983) who estimated global $CO_2$ emissions based on a broad sampling of UN fuel production numbers. Furthermore, all emission factors have been developed on a tonne per terajoule basis to facilitate comparisons of energy use with emissions of carbon.

## 3.1 Fuels

**3.1.1 Gaseous Fuels.** All fuel consumption figures for Canada have been taken from two Statistics Canada publications: Quarterly Report on Energy Supply-Demand in Canada, 57-003 (1988) and Crude Petroleum and Natural Gas Production, 26-006 (1988). A discussion of the quantities consumed can be found under the Emissions section in this report.

The determination of the carbon content of a fuel is usually based on the hydrocarbon fraction (in this case methane) of the fuel. Keeling (1973) calculated that the average carbon content of natural gas was 524 g of carbon/$m^3$. Subsequent work by Marland and Rotty (1983) has produced a more appropriate value. To develop an emission factor relating the consumption of natural gas in terms of its energy content to a mass unit of carbon, it is also necessary to determine an average heating value that is representative of Canadian gas.

Depending on the source of gas, its composition can vary greatly. Considine (1977) reports that the composition of high-BTU natural gas is approximately 95% methane, 4% nitrogen, and 1% heavier gases. It should also be noted that with the removal of natural gas liquids there is a reduction in the heating value of natural gas. Based on the U.S. reference gas shown in Table 2, assuming removal of 20% of the ethane, 72% of the propane, all of the heavier hydrocarbons, and all of the hydrogen sulphide ($H_2S$), carbon dioxide ($CO_2$) and water, Marland and Rotty (1983) have calculated that the resulting gas has a heating value of 9103 kcal/$m^3$. This dry gas contains 0.550 kg of carbon/$m^3$ at 0°C and with the separated $CO_2$ included, would produce 0.555 kg of carbon/$m^3$ when completely oxidized. At standard temperatures (15.6°C) this amounts to 525.4 g of carbon/$m^3$.

In performing similar calculations for a variety of natural gases (Table 3), Rotty and Marland (1983) found that the carbon content per unit energy could be closely represented by a linear relationship with heating value. This relationship is expressed by:

$$Cg = 57.357 + 1.459 \times 10^{-3} (\Delta HH - 8898) \qquad \text{Equation 1}$$

where: Cg is the amount of carbon (in g of carbon/1000 kcal); and

ΔHH is the higher heating value of the gas (in g of carbon/1000 kcal/$m^3$ at 15.6°C)

Due to differences in gas composition, many different calorific contents for natural gas can be and have been estimated and reported in the literature. The UN World Energy Supplies (1978) and (Hirschler, 1981) reported a value of 38.90 MJ/$m^3$. Using their regression equation and an upper end mean world value of 37.24 MJ/$m^3$, Marland and Rotty (1983) derived a value of 13.70 tonnes of carbon/terajoule as a mean world value for the carbon content of dry natural gas.

Although the National Energy Board (1986; 1988) publishes gross energy conversion factors (Table 4), the values given are not indicative of any year nor is there any means of determining what quantities were applicable to individual factors. Since Statistics Canada (57-003, 1988) provides conversion factors that are revised yearly and that take into account regional differences, their average heating value of 37.82 MJ/$m^3$ was chosen as a representative figure for natural gas consumed in Canada in 1987.

Substituting this value (37.82 MJ/$m^3$ or 9040 kcal/$m^3$) in Equation 1 yields 57.57 g of carbon/1000 kcal or 13.76 tonnes of carbon/terajoule. This result is similar to that derived by Marland and Rotty (1983) and one derived taking an average of the National Energy Board's values.

TABLE 2 COMPOSITION OF NATURAL GAS (% by volume)
(Marland and Rotty, 1983)

| | 1976 United States Reference Gas | Weighted World Mean | 1976 Adjusted Dry Gas |
|---|---|---|---|
| Methane | 88.32 | 89.24 | 92.88 |
| Ethane | 4.65 | 4.52 | 3.91 |
| Propane | 2.12 | 1.95 | 0.62 |
| Other HC's | 1.53 | 1.54 | -- |
| Carbon dioxide | 0.92 | 0.78 | -- |
| Other | 2.46 | 2.42 | 2.59 |
| Higher Heating Value ($kcal/m^3$) | 9685.60 | 9680.26 | 9102.62 |

TABLE 3 MEAN HEATING VALUE OF DRY NATURAL GAS
(Marland and Rotty, 1983)

| Year | United States ($kcal/m^3$) | World ($kcal/m^3$) |
|---|---|---|
| 1980 | - | 8825 |
| 1979 | 9068 | 8839 |
| 1978 | 9068 | 8851 |
| 1977 | 9086 | 8852 |
| 1976 | 9086 | 8864 |
| 1975 | 9112 | 8874 |
| 1974 | 9086 | 8893 |
| 1973 | 9139 | 8921 |
| 1972 | 9175 | 8924 |
| 1971 | 9175 | 8929 |
| 1970 | 9175 | 8956 |

The portion of fuel that does not undergo oxidization has been subtracted from this factor. For natural gas, the fraction of annual consumption that remains unoxidized each year is due to incomplete combustion. A fraction of the carbon in the gas used as fuel will remain in the stack, as soot around the burner, or be released into the environment. Although the exact amount of unoxidized carbon is difficult to quantify, a conservative estimate is about 1.5%.

The factor that has been used for estimating emissions of carbon dioxide from the combustion of natural gas (13.55 tonnes carbon/terajoule) has also been applied to

TABLE 4 GROSS ENERGY CONTENT FACTORS FOR NATURAL GAS (National Energy Board, 1986; 1988)

| | ($MJ/m^3$) |
|---|---|
| British Columbia | |
| - domestic | 39.10 |
| - Huntingdon | 39.10 |
| - Kingsgate | 37.65 |
| - Grassy Point | 38.20 |
| Alberta | |
| - domestic | 38.80 |
| - Cardston | 37.65 |
| - Aden | 36.06 |
| Eastern Canada | 37.65 |
| Canadian Average | 38.03 |

natural gas flaring. Although the carbon content, and therefore the energy content per gram of fuel, is lower for unprocessed gas, any error in applying the same factor is estimated to be less than that caused by the uncertainties associated with the oxidation assumptions.

**3.1.2 Liquid Fuels.** Petroleum derived liquids have been divided into eight different fuels, for which emission factors have been developed separately. As with natural gas, all liquid fuel consumption figures are from Statistics Canada publications 57-003 and 26-006. Expressed on a volume basis they can be found in the Emissions section of this report.

Brame and King (1967) report a range in composition of carbon in liquid petroleum products of (79% to 87%). Keeling (1973), has used an average of these values, 84%, while Marland and Rotty (1983) used 85%. According to Zimen et al. (1977), the carbon content of crude oil and natural gas liquids is approximately 95% by mass. With the exclusion of propane, the higher value reported by Keeling of 87% carbon by mass has been used in all the calculations in this report.

The various liquid fuels, their specific gravities, and gross energy content factors are listed in Table 5. The energy content factors have been taken from Statistics Canada (1988) and the National Energy Board (1986, 1988) while the range of specific gravities are from an oil industry conversion factor table, Modern Petroleum Technology (1975) and Perry and Chilton (1973).

TABLE 5 LIQUID FUELS

| Fuel | Specific Gravity Ranges | Gross Energy Content ($GJ/m^3$) |
|---|---|---|
| Motor gasolines | 0.71 to 0.79 | 34.66 |
| Aviation gasolines | 0.70 to 0.78 | 33.52 |
| Kerosenes | 0.78 to 0.84 | 37.68 |
| Diesel oils | 0.82 to 0.92 | 38.68 |
| Light oils | 0.85 to 0.95 | 38.68 |
| Heavy oils | 0.92 to 0.99 | 41.73 |
| Aviation Turbo | 0.78 to 0.84 | 35.93 |
| Propane | 0.508 | 25.53 |

To determine the fraction of liquid fuels that undergo oxidation, it is first necessary to estimate the portion which is not fully oxidized during combustion. An approximation has been made by comparing the 1985 emission estimates of volatile organic compounds (VOCs) and total suspended particulate (TSP) attributable to the combustion of liquid fuels, with the mass of liquid fuels combusted. Statistics Canada (1986) reported that in 1985, 54 514 000 tonnes of liquid fuels were consumed in Canada (see Table 6). The emissions of VOCs and TSP from the combustion of liquid fuels in 1985 were estimated to be 1 027 000 tonnes and 108 000 tonnes, respectively (Environment Canada, 1989). Carbon monoxide (CO), an incompletely oxidized material formed during combustion and discharged to the atmosphere, is assumed to undergo complete oxidation fairly rapidly (0.1 to 0.4 years) in the environment (Bach, 1988). Methane, another product of inefficient combustion, undergoes complete oxidation in some finite time (7 to 10 years), (Bach, 1988; Marland and Rotty, 1983). For this class of compounds, therefore, any difference between the total amount of carbon being oxidized in a given year and that which would be based on the full oxidation of a current year discharge, is a consequence of a change in annual fuel consumption and methane formation. Since the fraction of material in this class is small, the assumption that an equivalent fraction of material is oxidized each year should not introduce significant error.

Consequently, $1.135 \times 10^6$ tonnes or 2.1% of the total mass of fuels (the total of VOC and TSP emissions), represents the incompletely oxidized material from the combustion of liquid fuels. However, some fraction of this material undergoes oxidation over time. Many of the hydrocarbons emitted, especially from engine exhausts, are highly reactive (NRC, 1979). Data on urban aerosols show that their composition is in the order of 20% carbon (NRC, 1979); (Marland and Rotty, 1983). For these reasons, the fraction of

liquid fuel that undergoes combustion each year and remains in the environment unoxidized has been estimated to be 1.5%.

For each liquid fuel, emissions of $CO_2$, expressed as tonnes of carbon, were estimated by converting the energy contents of the fuels (Table 5) to a mass per energy unit. This was achieved by using the densities (Table 6) based on the median of the specific gravity ranges given in Table 5 and by multiplying the mass per energy unit by the appropriate carbon content and one minus the percent of the fuel unoxidized (i.e., 0.895). The emission factors derived this way are found in Table S.3.

A discussion of the emission estimates can be found in Section 4 of this report. In addition, the methodologies developed and used to aggregate emissions by vehicle type are also discussed.

TABLE 6 CONSUMPTION OF LIQUID FUELS IN CANADA (1985)

| Fuels | Volume ($10^3$ $m^3$) | Density ($t/m^3$) | Mass ($10^3$ t) |
|---|---|---|---|
| Motor gasoline | 32 732 | 0.75 | 24 549 |
| Kerosene | 860 | 0.81 | 697 |
| Diesel oil | 15 007 | 0.87 | 13 056 |
| Light oil | 7 344 | 0.90 | 6 609 |
| Heavy oil | 4 523 | 0.95 | 4 297 |
| Aviation gasoline | 177 | 0.74 | 131 |
| Aviation Turbo | 4 300 | 0.81 | 3 483 |
| Propane | 3 319 | 0.51 | 1 692 |
| Total | | | 54 514 |

**3.1.3 Solid Fuels.** As with gaseous and liquid fuels, emissions of $CO_2$ from the combustion of solid fuels are directly related to the quantity of fuel consumed, the carbon content of the fuel, and the fraction oxidized. The quantities of fuels consumed have been taken from Statistics Canada, Energy Supply-Demand, 1987. For coals, emission factors were developed for lignite, sub-bituminous, Canadian bituminous, U.S. bituminous, and anthracite. The carbon content, and therefore the energy content of coals can vary significantly. In order to develop emission factors that would represent a range of values for the coals used in Canada, several publications were consulted (Environment Canada, 1982; Canadian Electrical Association, 1985; Marks, 1978; Campbell, 1986). For the five coal types used in Canada, the weight percentage carbon contents (averages of values

found in above references) and energy contents (Statistics Canada, 1988) used in this report are given in Table 7.

TABLE 7 COALS CONSUMED IN CANADA

| Coal | Carbon Content (wt. %) | Gross Energy Content (GJ/t) |
|---|---|---|
| U.S. Bituminous | 71 | 29.00 |
| Canadian Bituminous | 70 | 27.60 |
| Sub-bituminous | 51 | 18.80 |
| Lignite | 43 | 14.40 |

In determining the fraction of carbon in coal that remains unoxidized, a similar method to that used by Marland and Rotty, 1983) and (CDIAC, 1988) has been adopted. In Canada, over 80% of the coal consumed is by power utility boilers. Consequently, using data on the products of combustion from these units should produce results that represent most of the coal consumed. An analysis of the bottom ash at the Battle River Generating Station (Canadian Electrical Association, 1985) showed an average carbon content of 5.5%, with the bottom ash averaging 12.25% of the total coal input. Based on these results, and an average carbon content of 50% in the coal, the total carbon remaining uncombusted in the ash is approximately 0.64%. An examination of data from the Tennesse Valley Authority's Bull Run Steam Plant (Marland and Rotty, 1983) showed that between 0.14 % and 2.7% of the combustible fraction of the coal remained unburned. Taking these results into consideration, it can be assumed that 1.0% of the carbon in coal, currently consumed in furnaces, is discharged unburned. The emission factors derived by multiplying the carbon content by the fraction oxidized and the appropriate energy content, are shown in Table S.3. It should be noted though, that emissions were estimated on a mass, not energy, basis.

For coal that is used for nonfuel purposes, an estimate of the fraction that does not undergo oxidation must also be made. Based on information supplied by the U.S. Department of Energy (1982) and Marland and Rotty (1983), on average, approximately 5.91% of the coal going to coke plants ends up as light oil and crude tar (Table 8). These coke by-products are used mainly in the chemical industry and as such do not undergo oxidation within the time period for which the emission estimates in this report are being made. The Canadian coke by-products industry is similar to that in the United States and

TABLE 8 LIGHT OIL AND TAR PRODUCED FROM COAL IN U.S. COKE PLANTS (CDIAC, 1988)

| Year | Crude Light Oil and Crude Tar ($10^6$ tonnes of coal equivalent by heating value) | Coal to Coke Plants ($10^6$ tonnes of coal equivalent by heating value) | % Coal Converted to Light Oil and Tar |
|---|---|---|---|
| 1980 | 3.29 | 54.88 | 6.00 |
| 1979 | 3.64 | 63.44 | 5.74 |
| 1978 | 3.34 | 58.75 | 5.68 |
| 1977 | 3.66 | 63.93 | 5.72 |
| 1976 | 3.95 | 69.69 | 5.68 |
| 1975 | 3.99 | 68.79 | 5.80 |
| 1974 | 4.24 | 74.22 | 5.71 |
| 1973 | 4.54 | 77.43 | 5.87 |
| 1972 | 4.57 | 72.16 | 6.33 |
| 1971 | 4.18 | 68.46 | 6.11 |
| 1970 | 4.76 | 79.40 | 6.00 |
| 1969 | 4.86 | 76.85 | 6.33 |

therefore, an adjustment has been made to the coal reported as consumed in producing coke that effectively reduces the quantities reported by 6.0%. For the adjusted coal figures, $CO_2$ emissions are calculated in a similar manner to those for coals used strictly as fuels.

The combustion of other solid fuels, such as fuel wood, refuse, and slash also produce emissions of $CO_2$. An emission factor for wood combustion and slash burning is easily calculated (Hirschler, 1981), if it is assumed that the chemical composition of wood is similar to that of cellulose (i.e., $C_6H_{12}O_6$) and that 100% combustion takes place. This gives an emission factor of 1.47 tonnes of $CO_2$ per tonne of wood combusted or 0.40 tonnes of carbon per tonne of wood combusted. Expressed on an energy basis, this becomes 22.22 t/TJ, based on an average gross energy content of 18 TJ/kt wood (Statistics Canada, 1988). The average thermal value of urban waste lies between 0.84 and 1.27 x $10^4$ kJ/kg (Burns and Seaman, 1973). An intermediate calorific value of 1.06 x $10^4$ kJ/kg corresponds to 37% of that of hard coal (Hirschler, 1981). Therefore, since the conversion of organic matter to carbon dioxide is responsible for virtually all the heat released by incinerated waste, the emission of carbon dioxide per tonne of refuse incinerated has been estimated as approximately 35% of that of each tonne of hard coal or 0.246 tonnes of carbon per tonne of refuse incinerated.

## 3.2 Industrial Processes

Cement and ammonia production are two industrial processes that emit significant quantities of carbon dioxide.

Cement is usually produced in a cement kiln in which calcium carbonate ($CaCO_3$) from a calcium rich material (limestone, chalk, or marl) is broken down into carbon dioxide and calcium oxide (CaO) which ultimately combines with the silicates in clay or shale to form dicalcium and tricalcium silicates (Helmuth et al., 1979). Calcium aluminates are also formed in Portland cement clinker. It is generally agreed, that the world average value of lime content in cement is between 60% and 67% (Orchard, 1973). Emissions have been estimated by using 63.5% as a fair value for the calcium oxide content in cement. A factor of 0.136 tonnes of carbon per tonne of cement produced has been obtained by dividing the molar mass of carbon dioxide by the molar mass of calcium oxide and multiplying this by the fraction of calcium oxide contained in the cement. This is the same value used by (Hirschler, 1981; Acres, 1987 and CDIAC 1988).

$$\frac{12.01 \text{ g/mole C}}{56.08 \text{ g/mole CaO}} \times 0.635 = 0.136 \text{ g Carbon / g cement}$$

Most of the ammonia ($NH_3$) produced in Canada is by the Haber-Bosh Process (Geadah, 1985). In this process, nitrogen and hydrogen are reacted in a 1 to 3 ratio at high temperature and pressure to produce ammonia. The hydrogen is obtained from natural gas. The material and energy requirements for the production of 1 tonne of ammonia are illustrated in Table 9 (Industrial Chemicals, 1980).

Based on this material balance and an assumption that all of the carbon contained in the natural gas is ultimately released to the environment, an emission factor relating carbon dioxide emissions to ammonia production has been developed. Assuming a carbon content of 525g/t of natural gas and 812 $m^3$ of natural gas are required for every tonne of ammonia produced, gives an emission factor of 0.426 tonnes of carbon per tonne of ammonia produced.

The pulp and paper industry is a major consumer of wood both in terms of the production of paper products and in the use of wood in producing energy. The major source of $CO_2$ from this industry is the combustion of spent pulping liquor (SPL). According to Statistics Canada's Energy Report (1988) the average energy content of SPL is about 14 TJ/t. A $CO_2$ emission factor for this industry has been estimated by assuming

TABLE 9 MATERIAL AND ENERGY REQUIREMENTS FOR AMMONIA PRODUCTION (Industrial Chemicals, 1980)
Basis - 1 tonne ammonia (liquified)

| | | |
|---|---|---|
| Natural gas (92% $CH_4$) | 812 | $m^3$ |
| Catalyst for shift reaction | 0.15 | kg |
| Synthesis catalyst | 0.25 | kg |
| Caustic soda (100%) | 4.00 | kg |
| Monoethanolamine | 0.15 | kg |
| Fuel gas (for driving compressors) | 7108 | kWh |
| Electricity | 119 | kWh |
| Water | 25 | $m^3$ |

the average carbon content of the liquors is 41% (Rydholm, 1965; McCubbin, 1983) and that all of the carbon contained in the fuel is released during combustion. Expressed in energy terms, this factor is 29.29 t/TJ. An analysis of the composition of waste liquors from different processes is found in Table 10.

TABLE 10 COMPOSITION OF PULPING WASTE LIQUORS (Rydholm, 1965)

| Total Solids | Acid Sulphite Rayon Pulp | Acid Sulphite Paper Pulp | Bisulphite Paper Pulp | Neutral Sulphite (semi-chemical) | Kraft |
|---|---|---|---|---|---|
| % of wood | 68 | 64 | 74 | 46 | 74 |
| % of waste liquor | 13 to 17 | 12 to 16 | 14 to 18 | 9 to 11 | 17 to 22 |
| Ashes, % of total solids | 10 to 12 | 12 to 14 | 18 to 20 | 35 to 45 | 35 to 45 |
| Carbon, % | 43 | 40 | 35 | 29 | 42 |
| Hydrogen, % | 5 | 5 | 4 | 4 | 5 |
| Oxygen, % | 42 | 42 | 42 | 44 | 35 |
| Sulphur, % | 6 | 8 | 11 | 8 | 3 |
| Sodium, % | 4 | 5 | 8 | 15 | 15 |
| Heat value, Mcal/t total solids | 4500 | 4300 | 3500 | 3000 | 3900 |

# 4 EMISSIONS

## 4.1 Industrial Processes

**4.1.1 Cement Production.** As previously stated, the production of cement generates significant quantities of $CO_2$. Dry and wet are the two methods used in Canada for cement manufacture, but regardless of the process employed, carbon is released during the reduction of calcium carbonate. In 1987, total cement production reported as producer shipments was 12 603 164 tonnes (EMR, 1988).

Based on an emission factor of 0.136 tonne of carbon per tonne of cement produced, total emissions from cement production were estimated at 1.71 Mt. Provincial emissions were estimated by prorating production capacities in each province by total production.

**4.1.2 Ammonia Production.** In Canada, most of the ammonia is produced by the Haber-Bosh process, where a mixture of gas containing nitrogen and hydrogen is reacted catalytically at high temperatures and pressures to produce ammonia. The nitrogen may be derived from the air by means of liquefaction, the producer gas reaction, or by burning out the oxygen in air with hydrogen. Hydrogen can be obtained from many sources, including water gas, coke-oven gas, natural gas, fuel oil, catalytic reformer gases and the electrolysis of water or brine (Industrial Chemicals, 1980).

To derive an emission factor, it has been assumed that most ammonia is produced using natural gas and that all of the carbon in the gas is eventually converted to $CO_2$ and removed. Based on these assumptions, and the required materials (see methodology) an emission factor of 0.426 tonnes of carbon per tonne of ammonia produced has been derived. Total emissions for 1987 have been estimated at 1.1 Mt of carbon based on ammonia production of 2590 kt (Corpus, 1987). Provincial emissions were estimated based on provincial capacities.

**4.1.3 Pulp and Paper Production.** As stated previously, emissions of $CO_2$ from the pulp and paper industry are mainly due to the combustion of spent pulping liquors. The two major chemical pulping processes are sulphite, which operates in a low pH or acid environment, and kraft, which is alkaline. Although the chemical composition of the various possible cooking liquors cover broad ranges (Table 10), the most dominant process is the kraft process. An average value between the acid sulphite and kraft process, therefore, has been chosen to be representative of the carbon content of spent pulping liquors. Quantities of spent pulping liquors were reported by Statistics Canada (1988).

Based on an average carbon content of 41% by weight in the spent pulping liquors, 20 639 kt of pulping liquors, 100% conversion to $CO_2$, emissions of carbon dioxide from the pulp and paper industry, expressed as tonnes of carbon, were estimated to be 8.46 Mt in 1987. Provincial emissions were estimated, partially based on reported values. For provinces in which production figures were grouped by region, values were estimated through comparison with the 1980 carbon monoxide emissions (Environment Canada, 1986).

## 4.2 Fuel Combustion - Stationary Sources

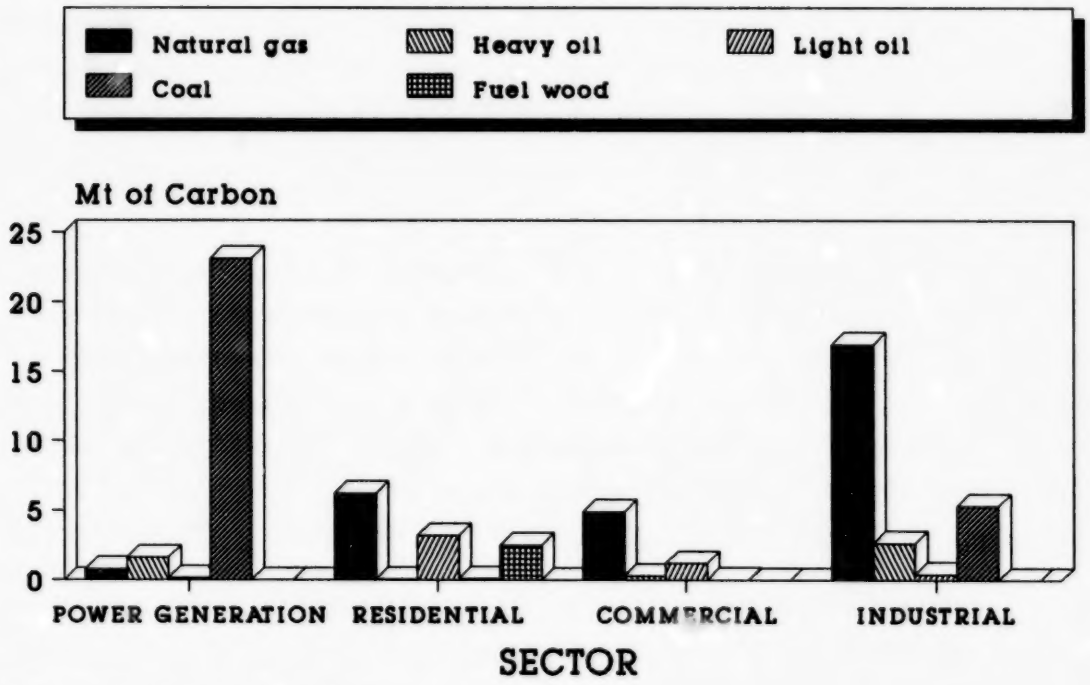
**4.2.1 Power Generation.** In 1987, electricity generated by coal-fired stations accounted for 47.52% of total thermal generation; oil-fired, 5.13%; natural gas, 4.2%; and nuclear, 43.15%. Hydro-powered generation accounted for 64.96% of the total generation of 482 108 GWh (EMR, 1988 b). Nuclear and hydro-powered generation are not emitters of carbon dioxide.

Two basic systems are used to generate thermal power from fossil fuels: steam generation, and internal combustion (gas turbine and reciprocating engines). Steam turbine boilers are fired with coal, heavy fuel oil, crude oil, or natural gas (initial steam may be raised by light fuel oil, natural gas, kerosene, or diesel oil), whereas reciprocating engines use light oil, natural gas, a combination of both, or diesel oil.

Emissions of carbon dioxide have been estimated based on the quantities of fossil fuels consumed in producing electricity, taking into account the type of fuel, its energy content, carbon content, and the fraction oxidized (see Figure 3). The methods used have been described in detail in Section 3 and the emission factors derived are given in Table S.3. Based on these emission factors and the quantities of fuels consumed (41 883 kt of coal, 1 912 000 $m^3$ of heavy oil, 176 800 $m^3$ of light oil, 1.5 x $10^9$ $m^3$ of natural gas, and 240 000 $m^3$ of diesel oil (Statistics Canada, 1988), total emissions of carbon dioxide from fossil fuel-fired generated electricity were estimated to be 25.76 x $10^6$ t of carbon, or about 20% of the total man-made emissions in 1987.

**4.2.2 Fuel Combustion.**

**Industrial.** The amounts of fuel used for industrial purposes in 1987 are reported in Table 11 (Statistics Canada, 1988). An additional 12 x $10^9$ $m^3$ of natural gas was consumed by industrial producers and reported as producer consumption. In addition, 5930 kt of coal used in coke production was also included in this sector (Statistics Canada, 1988).




Excludes diesel, kerosene & propane

FIGURE 3 CARBON DIOXIDE EMISSIONS FROM STATIONARY SOURCES

TABLE 11 1987 FUEL CONSUMPTION BY STATIONARY SOURCES (Statistics Canada, 1988; Environment Canada, 1989)

| Sources of Fuel Combustion | Fuel Consumption | | | | | | |
|---|---|---|---|---|---|---|---|
| | coal (kt) | natural gas ($m^3$) | heavy oil ($m^3$) | kerosene and stove oil ($m^3$) | propane ($m^3$) | light oil ($m^3$) | wood (kt) |
| Industrial | 1735 | $2.1 \times 10^{10}$ | 3 261 300 | 50 700 | 537 300 | 538 300 | - |
| Commercial | 26 | $8.6 \times 10^{9}$ | 235 800 | 100 200 | 554 300 | 1 104 300 | - |
| Residential | 174 | $1.2 \times 10^{10}$ | 65 500 | 489 800 | 1 105 600 | 4 104 300 | 6244 |
| Other (agriculture; public administration) | 0.6 | $9.55 \times 10^{8}$ | 122 000 | 78 000 | 1 969 000 | 465 000 | - |

Carbon dioxide emissions of 25.6 Mt were calculated using the emission factors given in Table S.3.

**Commercial.** Consumption of fuels for commercial use is reported in Table 11. As with industrial fuel combustion, emissions of 5.8 Mt were calculated using the emission factors derived in Section 3.

**Residential.** Based on the consumption quantities reported in Table 11, emissions of $CO_2$ expressed as tonnes of carbon, were estimated at 12.8 Mt.

**Other Fuel Combustion Sources.** Included in this category are non-transporation fuels reported by Statistics Canada as consumed in agriculture and public administration. The consumption of fuels for other combustion sources is shown in Table 11.

Emissions for this category were estimated at 1.1 Mt in 1987. Total emissions from all stationary combustion sources were estimated at 71 Mt.

## 4.3 Fuel Combustion - Transportation

Emissions evolve from fuel combusted for transportation. The carbon dioxide emissions from gasoline-powered and diesel-powered road motor vehicles, aircraft, rail transport, marine transport, off-road, and other fuel uses are depicted in Figure 4.

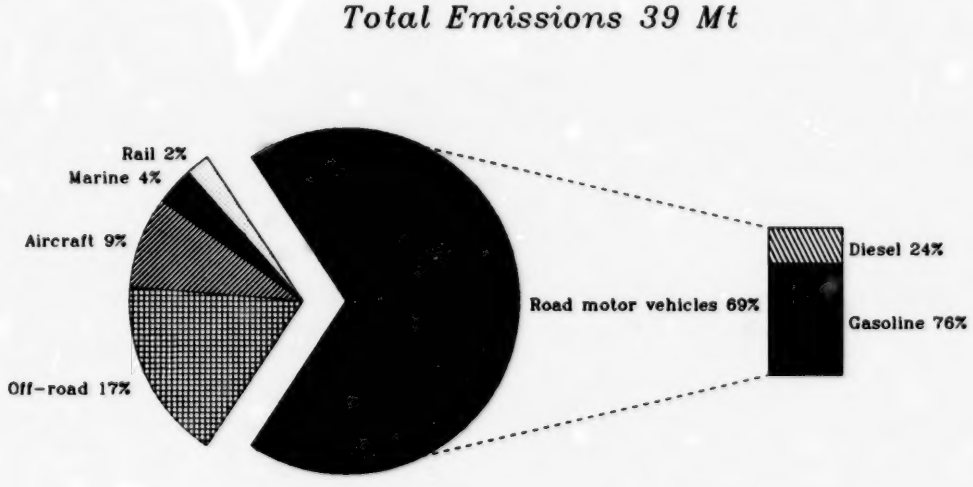



FIGURE 4 CARBON DIOXIDE EMISSIONS FROM TRANSPORTATION SOURCES

**4.3.1 Gasoline-powered Road Motor Vehicles.** Emissions from all gasoline-powered vehicles driven on public roads, including automobiles, trucks, buses, and motorcycles are discussed in this section.

The emission factor used to estimate emissions for all motor vehicles consuming gasoline is 18.54 t/TJ (see Section 3 - Liquids). The derivation of this factor is quite straightforward and assumes a certain percentage of the carbon in the fuel is eventually emitted and forms $CO_2$. The fraction of carbon in the fuel that is released as CO ideally should be between 0.6% and 1.2% of the carbon released as $CO_2$ (Environment Canada, 1989). Although in actual use the percentage is higher due to the inherent inefficiencies of the internal combustion engine, it has been assumed that the fraction of carbon released as CO eventually forms $CO_2$.

Methane and other organics are released in much smaller quantities than $CO_2$ and as such their inclusion or exclusion is estimated to affect the estimates much less than any errors inherent in the emission factors. A more detailed discussion of the assumptions made is given in Section 3 - Methodology. The separation of emissions by vehicle type is much more difficult.

Based on the fuel usage figures provided by Statistics Canada (1988), emissions were broken down into on-road and off-road uses of gasoline. On-road uses are assumed to be made up of commercial uses, road transport, and retail pump sales. Off-road estimates include construction, forestry, and agricultural uses. To further segregate emissions within these categories, specifically the on-road group, it was necessary to make some assumptions concerning vehicle fuel efficiencies.

Based on Dupont's Escon computer model (Du Pont, 1983) fleet average fuel efficiencies were derived for automobiles, light-duty trucks, heavy-duty trucks, and motorcycles and were estimated to be 8.5 km/L, 4.71 km/L, 2.62 km/L, and 14.18 km/L respectively. To determine how well these factors represented the actual fleet, an indirect comparison was made by estimating the quantities of fuels consumed in 1985. Several calculations were made using the Statistics Canada derived vehicle population figures and estimates of miles driven by each vehicle type. The calculated quantities of gasoline consumed agreed within 1% of the reported consumption figures (Statistics Canada, 1986;. A summary of the figures used in the calculations can be found in Table 12.

The gasoline usage splits obtained from the preceding calculations were: autos, 65.10%; light-duty trucks, 27.51%; heavy-duty trucks, 7.14%; and motorcycles, 0.29%. These percentage splits were then applied to the on-road gasoline figures for 1987. Total

emissions from on-road, gasoline-powered vehicles in 1987 were estimated to be 20.27 Mt of carbon.

**4.3.2 Diesel-powered Road Motor Vehicles.** Emissions of $CO_2$ from all diesel-powered vehicles driven on public roads, including automobiles, trucks and buses have been estimated using a similar methodology to that used for gasoline-powered road motor vehicles. Based on the vehicle splits obtained (Table 12), LDDV-10.02% and HDDV-89.98%, and an emission factor of 19.28 t/TJ, 1987 emissions of $CO_2$ were calculated for these two classes of vehicles. Total emissions were estimated to be 6.5 Mt of carbon in 1987.

TABLE 12 GASOLINE / DIESEL OIL CONSUMPTION - 1985 ROAD MOTOR VEHICLES

| Vehicle | Population | Distance Driven (km) | Mileage (km/L) | Consumption (GL) |
|---|---|---|---|---|
| Automobiles | 11 118 071 | 15 289 | 8.50 | 19.96 |
| Light-duty gasoline vehicles | 2 244 085 | 17 703 | 4.71 | 8.44 |
| Heavy-duty gasoline vehicles | 285 646 | 20 117 | 2.62 | 2.19 |
| Light-duty diesel vehicles | 201 588 | 17 703 | 5.90 | 0.61 |
| Heavy-duty diesel vehicles | 216 353 | 82 881 | 3.28 | 5.48 |
| Motorcycles | 470 445 | 2 816 | 14.18 | 0.09 |

**4.3.3 Off-road Use of Gasoline.** Gasoline consumed in off-road use is defined as that which is not consumed by road vehicles and includes gasoline consumed by construction equipment, agricultural equipment, forestry equipment, and general utility equipment. Approximately 5% of the gasoline sold in Canada in 1987 was consumed by off-road vehicles and amounted to approximately $1.7 \times 10^9$ L. Emissions of carbon dioxide expressed as carbon were estimated to be 1.1 Mt based on the general emission factor derived for gasoline (18.54 t/TJ).

**4.3.4 Aircraft.** Two main types of aircraft are considered here: reciprocating (piston) and gas turbine. Both types are further divided into subclasses depending on the size of the aircraft and the most commonly used engine for that class. The types of

aircraft included in this section are: jets, turboprops, piston-engined planes, and helicopters.

Carbon dioxide emissions have been estimated based solely on fuel consumption figures reported by Statistics Canada (1988) and the emission factors previously derived. Based on emission factors of 18.92 and 19.32 t/TJ and fuel quantities of 177.2 and 4659.4 ML for aviation gasoline and jet fuel respectively, emissions were estimated to be 3.3 Mt in 1987.

**4.3.5 Rail Transport.** Emissions from rail transport are based on the quantities of fuels consumed in the production of energy for locomotion. Based on the quantities of diesel oil reported to be consumed by rail transport (Statistics Canada, 1988), and an emission factor of 19.28 t/TJ or 0.75 $t/m^3$, total emissions of $CO_2$ as carbon from rail transport were estimated to be 1.47 Mt or 1.15% of total emissions.

**4.3.6 Marine Transport.** Only ships that use diesel oil and heavy oil have been considered in this section. Statistics on gasoline consumption for marine uses were not available from retail sales figures and therefore, emissions from these sources have been included in the off road gasoline category.

Based on emission factors of 19.28 and 19.51 t/TJ for diesel oil and heavy oil respectively, 1987 emissions have been estimated to be 1.4 Mt of carbon.

**4.3.7 Other Diesel-powered Vehicles.** Carbon dioxide emissions from diesel-powered engines used in the mining, manufacturing, forestry, public administration, construction, and agricultural sectors of the economy were estimated using a diesel oil emission factor of 19.28 t/TJ and applying it to the quantities of fuels reported to have been consumed by these industry sectors (Statistics Canada, 1988).

In 1987, total emissions from other diesel engines were approximately 3.8 Mt of $CO_2$, expressed as carbon.

**4.3.8 Other Fuel Uses.** Carbon dioxide emissions from the combustion of natural gas and propane were estimated based on reported figures of energy use for transportation purposes (Statistics Canada, 1988) and emission factors of 13.55 t/TJ for natural gas and 16.32 t/TJ for propane. Due to insufficient data, no attempt was made to split these emissions among different vehicle types.

Total emissions were estimated at 1.7 Mt of carbon from these sources in 1987.

## 4.4 Emissions From Waste Incineration

**4.4.1 Municipal Refuse Incineration.** Municipal incineration is a process that reduces the volume of solid waste by burning. Some incinerators are best suited for incineration of a waste with particular physical characteristics. Typical municipal refuse incinerators consist of either refractory-lined or water-walled combustion chambers with a grate upon which refuse is burned.

The emission of $CO_2$ from the combustion of urban waste depends almost entirely on the carbon content and therefore energy content of the waste. Based on an emission factor of 0.246 t of carbon per tonne of waste incinerated and approximately 909 000 tonnes of municipal refuse incinerated (Environment Canada, 1989) emissions were estimated at 0.22 Mt.

**4.4.2 Industrial Incineration.** Industrial and commercial incinerators are usually of an intermediate size, capable of burning from 25 to 1800 kg of refuse per hour. The most common design used has a multiple chamber in which gases from the primary chamber flow to smaller secondary mixing chamber where excess air is admitted to promote more complete combustion.

While approximately 75% of the waste is assumed to be incinerated in a multiple chamber incinerator, the remainder is disposed of in controlled air type incinerators. These incinerators operate by burning refuse in the absence of sufficient oxygen necessary. Combustion is then completed in a secondary chamber by introducing excess air.

Emissions from the incineration of industrial wastes have been estimated in a similar manner as those from municipal incinerators and are based on the incineration of approximately 505 100 tonnes of waste material (Environment Canada, 1989). Emissions were estimated to be 0.14 Mt.

**4.4.3 Wood Waste Incineration.** Wigwam burners are used for the disposal of sawdust in the lumber and plywood industries. An estimate of the amount of waste wood disposed of was determined based on the quantity of lumber produced (Environment Canada, 1989) and was estimated to be about 6 Mt.

Emissions of $CO_2$ were calculated using the derived emission factor for wood combustion of 0.4 tonnes of carbon per tonne of wood waste incinerated and were estimated to be 2.4 Mt.

## 4.5 Miscellaneous Sources

**4.5.1 Slash Burning.** Recent data on emissions of $CO_2$ from slash burning and forest fires were not available so estimates were based on 1985 figures.

Slash is burned for three main reasons: to reduce the hazard of forest fires, to promote the growth of seedlings, and to control insects. Approximately $10.7 \times 10^6$ tonnes of slash were burned in 1985 and this corresponds to about 4.3 Mt of carbon. Information on the quantity of slash burned in Canada was based on primary forest production and emissions were estimated from the $CO_2$ emission factor for wood (Environment Canada, 1989).

**4.5.2 Forest Fires.** Although not considered a man-made source of emissions, forest fires are nevertheless a major source of carbon dioxide. In 1986, approximately 624 115 ha of forest in Canada were consumed by fire (CFS, 1986). This translates to about $14 \times 10^6$ tonnes of wood and based on this, emissions of $CO_2$ as carbon were estimated to be 5.5 Mt.

## 5 FOREST BIOMASS IN CANADA

If only fossil-fuel derived emissions of $CO_2$ were examined in this report, it would be of little interest to discuss other sources, including wood combustion. In terms of contribution to total energy needs, however, biomass has been estimated to contribute about 4% (EMR, 1989) not, as some have contended, an insignificant fraction. Regardless of their contribution, however, quantification of all man-made sources of carbon dioxide emissions must include those from wood combustion. Whether or not an accurate estimate of the contribution from forest harvesting and regeneration practices can be made, burning wood does have a net effect on total emissions of $CO_2$. To illustrate this, several calculations have been made using Canadian forestry statistics (Kuhnke, 1989). From 1983-84 to 1985-86, approximately 1 965 353 ha of forest were harvested and 1 438 647 ha regenerated through planting, seeding, and natural process (Kuhnke, 1989).

Annual forest growth rates in Canada vary from 0.2 to 5.7 $m^3$/ha with an overall average of 1.5 $m^3$/ha (Power, 1989). The growth rate of trees is a function of site and stand attributes such as species, structure, age, climate, water and nutrient availability, and silviculture practices. In order to make gross estimates of carbon dioxide uptake it is necessary to use an average value.

Based on an annual average growth rate of 1.5 $m^3$/ha, an average density for spruce and pine of 631 kg/$m^3$, and an average carbon content of 39%, it is estimated that approximately 369 kg of carbon are consumed for every hectare of forest in Canada. Closed forests in Canada cover approximately 264 x $10^6$ ha (World Resources, 1986), thereby taking up about 97 Mt of carbon as $CO_2$. Annual regeneration of harvested forests takes up an additional 177 kt of carbon. It is clear, therefore, that the total $CO_2$ uptake as carbon from forest growth, is due almost entirely to existing forests.

If it is assumed that natural uptake of $CO_2$ by forests has been constant over the last 100 years, and has remained in balance with emissions of $CO_2$ from natural sources, then it is only the growth of new forests that should be considered as a sink for $CO_2$ produced by mans' activities. Slash burning alone contributes about 4.3 Mt of carbon as $CO_2$ to the atmosphere and consequently the annual uptake of 0.18 Mt from reforestation practices pales beside the total emissions of $CO_2$ from all forms of wood combustion. If silviculture practices were implemented to provide ideal forest growth conditions (i.e., 5.7 $m^3$/ha) throughout Canada, an additional 91 x $10^6$ ha of forest would be required to offset total man-made emissions. Clearly, forest regeneration alone will not balance the carbon budget, though it can play a role in reducing net emissions.

## 6 EMISSION TRENDS

Emissions of $CO_2$ have been estimated for the years 1985 to 2005 (Sheffield, 1989) based on the National Energy Board's projected growth rates for energy demand in all major industry sectors (NEB, 1988). All growth rates are based on the NEB's "high growth" scenario. The emission factors used are the same as those developed in this report and they are assumed constant throughout the projected time period.

For the sectors not identified by the National Energy Board, Informetrica growth rates were used, based on their most recent economic model (TIM).

As illustrated in Figure 5, total emissions in Canada are projected to increase approximately 38% in the next 18 years from 128 Mt in 1987 to about 177 Mt in 2005.

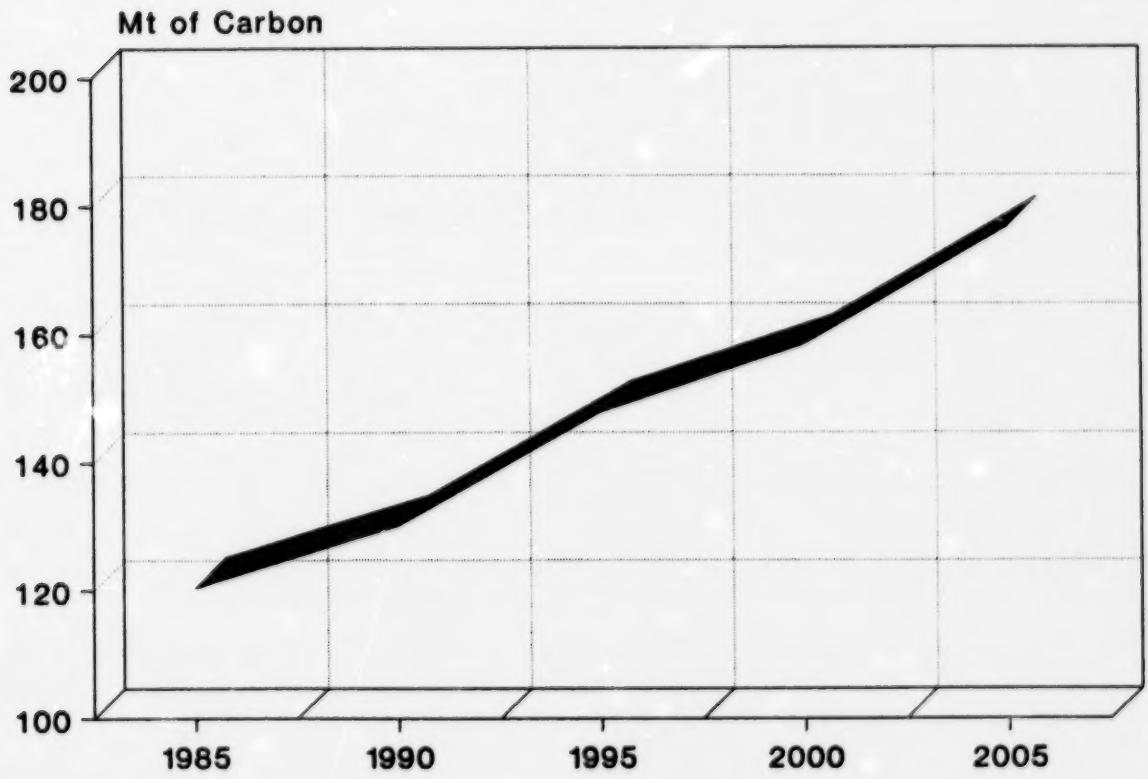



FIGURE 5 CARBON DIOXIDE EMISSION TRENDS (1985-2005)

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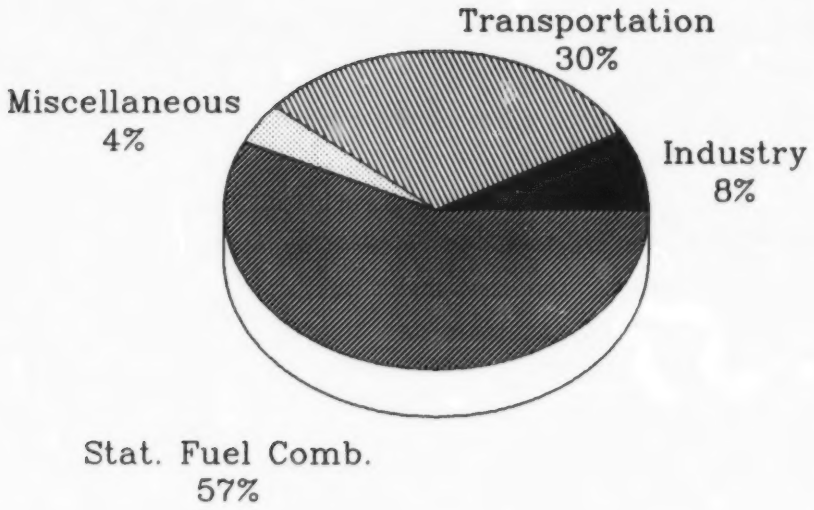
# APPENDIX

## CARBON DIOXIDE EMISSIONS BY REGION

## APPENDIX CARBON DIOXIDE EMISSIONS BY REGION

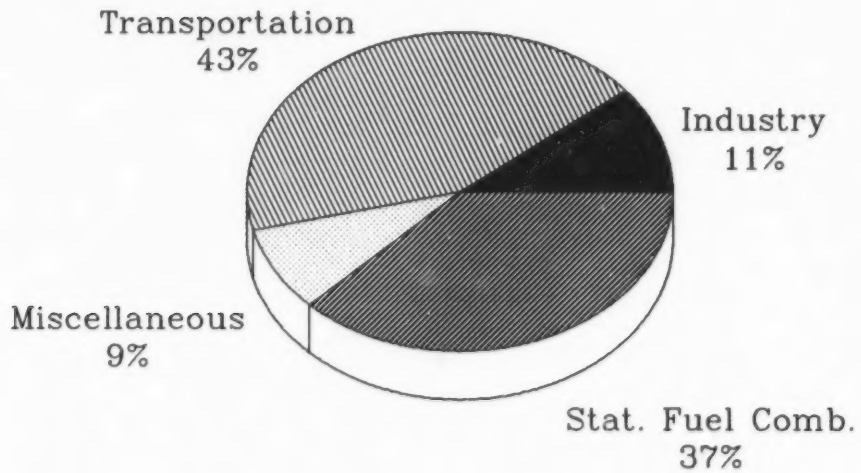
The following pie charts represent the emissions of $CO_2$ (as carbon) by sector and region in Canada for 1987.

The charts clearly show that there are wide differences in the major sources of $CO_2$ emissions among some regions. In British Columbia, for example, there is an almost equal distribution among the four major sectors. Stationary Fuel Combustion sources dominate in Ontario, Saskatchewan, and Alberta where they account for 61, 67 and 75% of the total, respectively.



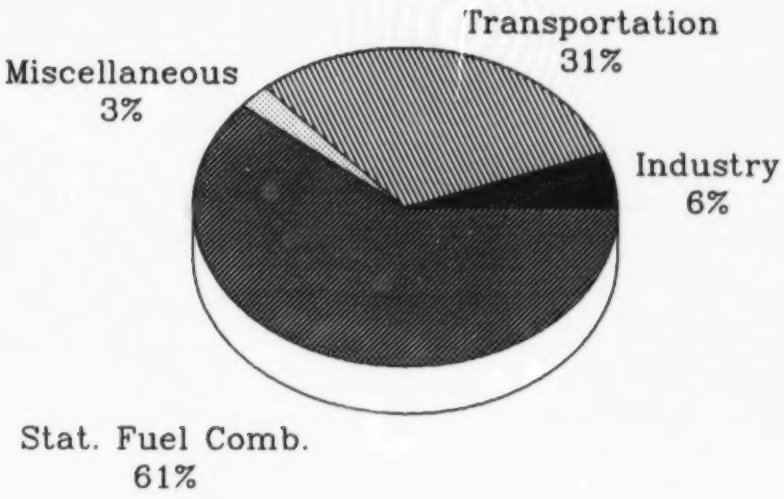

TOTAL EMISSIONS 11 Mt

FIGURE A.1 CARBON DIOXIDE EMISSIONS BY SECTOR -- ATLANTIC REGION



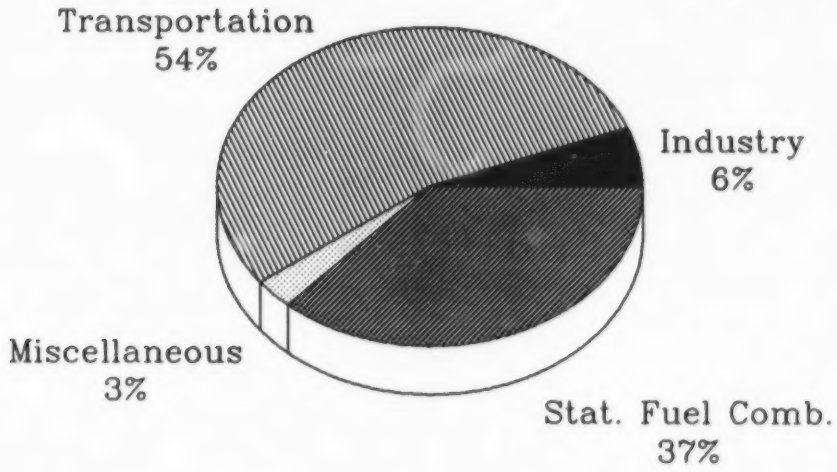

TOTAL EMISSIONS 17 Mt

FIGURE A.2 CARBON DIOXIDE EMISSIONS BY SECTOR -- QUEBEC



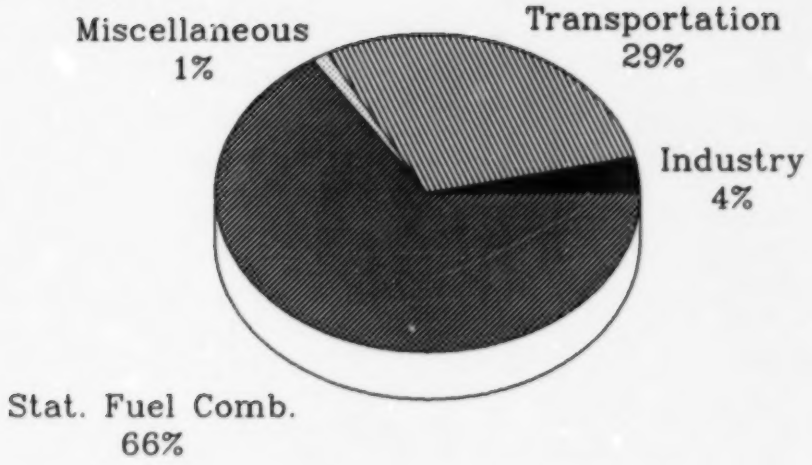

TOTAL EMISSIONS 42 Mt

FIGURE A.3 CARBON DIOXIDE EMISSIONS BY SECTOR – ONTARIO



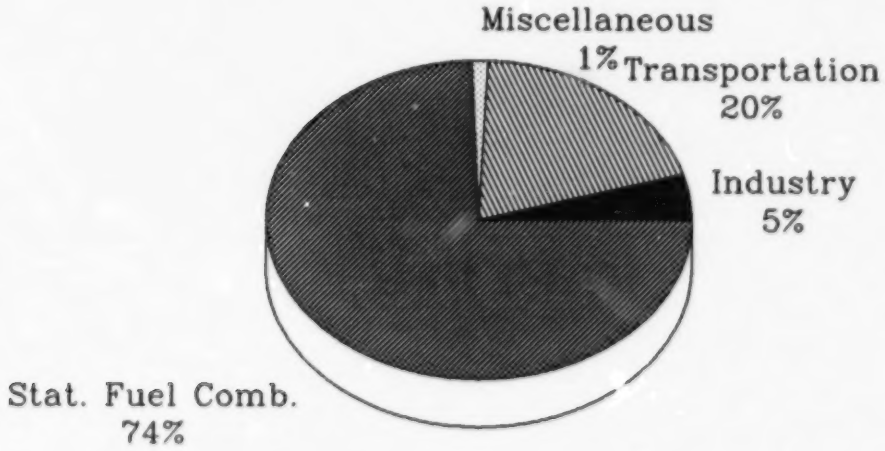

TOTAL EMISSIONS 3 Mt

FIGURE A.4 CARBON DIOXIDE EMISSIONS BY SECTOR – MANITOBA



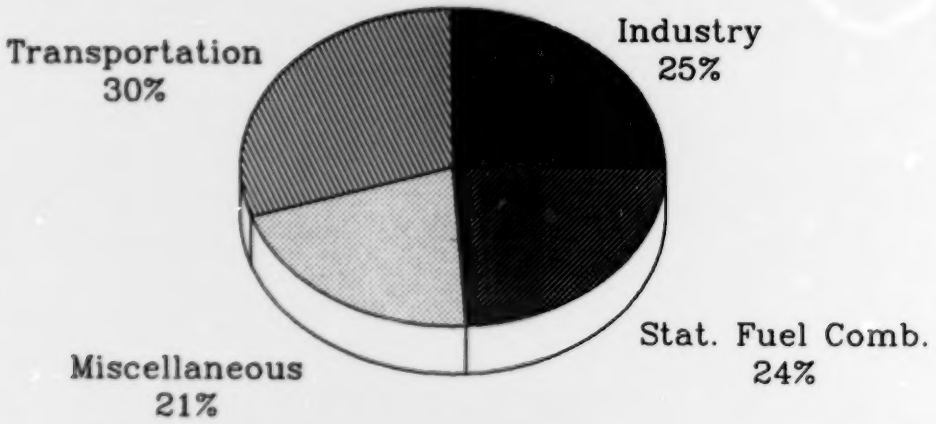

TOTAL EMISSIONS 8 Mt

FIGURE A.5 CARBON DIOXIDE EMISSIONS BY SECTOR -- SASKATCHEWAN




TOTAL EMISSIONS 29 Mt

FIGURE A.6 CARBON DIOXIDE EMISSIONS BY SECTOR -- ALBERTA




TOTAL EMISSIONS 17 Mt

FIGURE A.7 CARBON DIOXIDE EMISSIONS BY SECTOR -- BRITISH COLUMBIA